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NASA CASE NO. LAR 14850-1-CU

PRINT FIG. 1

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10-29-92 LaRC

(NASA-Case-LAR-14850-1-CU) RAPID DETECTION AND QUANTIFICATION OF FEATURES SUCH AS DAMAGE OR FLAWS IN COMPOSITE AND METALLIC STRUCTURES Patent Application (NASA) 27 p

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RAPID DETECTION AND QUANTIFICATION OF FEATURES SUCH AS DAMAGE OR FLAWS IN COMPOSITE AND METALLIC STRUCTURES

The present invention relates generally to a non-destructive evaluation (NDE) apparatus, system and method for facilitating detection, quantification and/or evaluation of a feature in a material, or more specifically, to an apparatus, system and method for facilitating rapid and effective detection, quantification and/or evaluation of a feature such as damage or a flaw in a material including composite or metallic materials.

In Figure 3, thermographic unit 1 utilizes thermography to obtain relatively rapid detection and/or the capability to rapidly locate a feature such as, for example, damage or a flaw, in a material of a relatively large size, and ultrasonic unit 11 of Figure 9 uses ultrasound to specifically locate the feature for effective quantification and/or evaluation using the relatively high resolution afforded by ultrasound.

The use of thermography and ultrasound in tandem to perform NDE is expected to provide several advantages. In structures such as aircraft in which the size of a material to be scanned is relatively large and in which the resolution of any feature detected is required to be relatively precise, the present invention is expected to be particularly effective. Also, the present invention can be used to scan a material from only one side thereof, and thus, is expected to be relatively portable and practical to use. In addition, the present invention is expected to provide relatively less expensive NDE capabilities.

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RAPID DETECTION AND QUANTIFICATION OF FEATURES SUCH AS DAMAGE OR FLAWS IN COMPOSITE AND METALLIC STRUCTURES

Origin of the Invention

The invention described herein was made by employees of the U.S. Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

Background of the Invention

Field of the Invention

The present invention relates generally to an apparatus, system and method for facilitating detection, quantification and/or evaluation of a feature in a material, or more specifically, to an apparatus, system and method for facilitating rapid and effective detection, quantification and/or evaluation of a feature such as damage or a flaw in a material including, but not limited to, composite or metallic materials.

Description of the Related Art

There are many types of conventional non-destructive evaluation (NDE) devices and techniques for evaluating physical characteristics of a material, for example, to detect flaws or damage in the material. Such conventional devices and techniques vary from relatively unsophisticated types of NDE (e.g., tapping) to relatively sophisticated types of NDE (e.g., computerized tomography (CT) scan).

Conventional NDE devices and techniques, however, are not effective

for applications in which the size of the material to be evaluated is relatively large, and in which a relatively high resolution of a feature in the material, such as damage or a flaw, is required to effectively detect, quantify and/or evaluate the feature. In general, an NDE device or technique which has a relatively high resolution also requires a relatively long time to operate and/or requires equipment which is impossible or impractical to use for evaluating either a particular configuration of a material or a relatively large amount of material such as, for example, that included in the structure of a helicopter or aircraft.

Further, in applications requiring rapid, high-resolution NDE in particularly-configured or relatively large-sized materials, the deficiencies of conventional NDE devices and techniques discussed above can be magnified by the type of material involved. Composite materials, which are being used with increasing frequency in a variety of applications, exhibit significantly different damage or failure mechanisms than comparable metallic materials due to their laminated construction and comparatively weak (in general) through-the-thickness (TTT) physical properties. Also, composite materials often have a three-dimensional architecture to enhance damage tolerance. For example, referring to Figures 1 and 2, a flat panel and a "Y"-stiffened panel, respectively, are fabricated from composite materials with a three-dimensional architecture. Such three-dimensional architecture renders detection and quantification of a feature such as damage in the composite material relatively difficult because, for example, a composite material is capable of exhibiting no visible front damage and yet having significant internal damage which can render the composite material unusable for a particular application. Further, since composite materials are expected to make extensive use of cocuring or adhesive binding of structural elements to eliminate the cost associated with mechanical fastening, disbonds between stiffeners and skin elements in composite materials can occur from manufacturing anomalies, excessive loads and/or as a result of foreign object damage. Therefore, while many conventional NDE devices and techniques are suitable for detecting and

quantifying and/or evaluating a metallic material, such conventional NDE devices and techniques can be ineffective for evaluating features of interest in a composite material, and further, are ineffective for evaluating features of interest in a composite material of large size.

Summary of the Invention

It is an object of the present invention to provide an apparatus, system and method for facilitating relatively rapid and effective detection, and quantification and/or evaluation of a feature in a material.

Another object of the present invention is to provide an apparatus, system and method for facilitating relatively rapid and effective detection, quantification and/or evaluation of a feature such as damage or a defect, in a material having a relatively large size.

Another object of the present invention is to provide an apparatus, system and method for facilitating relatively rapid and effective detection, quantification and/or evaluation of a feature such as damage or a defect, in a composite material.

Another object of the present invention is to provide an apparatus, system and method for facilitating relatively rapid and effective detection, quantification and/or evaluation of a feature in a material from only one side thereof.

Another object of the present invention is to provide an apparatus, system and method for facilitating relatively rapid and effective detection, quantification and/or evaluation of a feature in a material, which is relatively inexpensive.

Another object of the present invention is to provide an apparatus, system and method for facilitating relatively rapid and effective detection, quantification and/or evaluation of a feature in a material, which is relatively portable.

In order to achieve the foregoing and other objects, in accordance with the purposes of the present invention as described herein, an apparatus for analyzing a material is provided with a heat source for heating the material, and a heat detector for detecting heat emanated from the material, and for generating a heat signal based on the heat. The apparatus is also provided with an ultrasonic source for transmitting a source signal to the material, and an ultrasonic receiver for generating a received signal based on the source signal echoed from the material. The heat signal is used to detect and/or generally locate a feature in the material, and the source signal is used to specifically locate the feature. Also, at least one processor can be provided to generate a display based on the heat signal and/or the received signal. Further, a display unit can be used for displaying the display so that an external device or an operator can quantify and/or evaluate the feature such as damage or a defect, in the material.

These and other features and advantages of the present invention will become more apparent with reference to the following detailed description and drawings. However, the drawings and description are merely illustrative in nature and not restrictive.

Brief Description of the Drawings

Figure 1 is a diagram of a flat panel fabricated from composite materials;

Figure 2 is a diagram of a "Y"-stiffened panel fabricated from composite materials;

Figure 3 is a diagram of a thermographic unit 1 in accordance with the present invention;

Figure 4 is a flow chart of image processing to obtain tiles which can be performed by a processor 5, in accordance with the present invention;

Figure 5 is a flow chart of processing to terminate the image processing of Figure 4;

Figure 6 is a flow chart of image processing which can be performed by the processor 5 to eliminate a background image from tiles obtained in the image processing of Figure 4, in accordance with the present invention;

Figure 7 is a flow chart of image processing to terminate the image processing of Figure 6;

Figure 8 is a flow chart of image processing to normalize the tiles obtained in the image processing of Figures 4-7, in accordance with the present invention;

Figure 9 is a diagram of an ultrasonic unit 11, in accordance with the present invention;

Figure 10 is a flow chart of image processing performed by the processor 14, in accordance with the present invention;

Figure 11 is a graph of the magnitude of the analytic transfer sequence $h_A(m)$ versus m;

Figure 12 is a diagram of a series of displays for the depths A-H of Figure 11;

Figure 13 is a diagram of a series of thermographic and ultrasonic displays for damage in the flat panel of Figure 1 caused by various impact energies of an aluminum ball;

Figure 14 is a diagram of a conceivable realization of the thermographic unit 1 of Figure 3; and

Figure 15 is a diagram of a conceivable realization of the ultrasonic unit 11 of Figure 9, which can incorporate most of the elements of thermographic unit 1 of Figure 14.

Detailed Description of the Preferred Embodiments

In general, the present invention utilizes thermography to obtain relatively rapid detection and/or the capability to generally and rapidly locate or scan a feature such as damage in a material of relatively large size, and uses

ultrasound to specifically locate or scan the feature for effective quantification and/or evaluation using the relatively high resolution afforded by ultrasound. While specific embodiments of the apparatus, system and method of the present invention are described below, it is intended for that the present invention encompass a combination of a thermographic apparatus, system or method with an ultrasonic apparatus, system or method, whether conventional or otherwise.

Figure 3 is a diagram of a thermographic unit 1 in accordance with the present invention. The thermographic unit 1 functions to heat a material, and to provide data to detect or generally locate a feature of interest in the material by monitoring heat from the material as it cools. Because a material back-scatters heat incident thereto throughout its thickness in dependence upon the type of material and the absence or presence of a feature (e.g., damage) in the material, a response of a material subjected to rapid heating yields information concerning the presence or absence and/or general location of a feature therein. In other words, the distribution of heat from a surface of the material over time indicates the physical characteristics of the material at a depth corresponding to the time elapsed from the rapid heating of the material. Therefore, the thermographic unit 1 is capable of detecting and/or generally locating a feature at a depth within the material 3, and providing three-dimensional positional information concerning the feature.

To accomplish the purposes indicated above, the thermographic unit 1 is provided with a heat source 2 which is arranged in proximity to the material 3 and which is operable to heat the material 3. The heat source 2 can include a photographic flash lamp composed of a "Starflash 3 power supply" and a "Z bi-tube model head", catalog number 10-0555, manufactured by Balcar, Incorporated. A heat detector 4 is arranged in proximity to the material 3 and generates a heat signal based on heat received from the material 3. The heat detector 4 can include an infrared camera such as a "Model 600" manufactured by Inframetrics, Incorporated. Preferably, the "Model 600" is operated in a

wavelength range from 8 to 14 micrometers.

The heat signal from the heat detector 4 is provided to processor 5 via, for example, a video cable. The processor 5 controls the overall operation of the thermographic unit 1, and generates a display using the heat signal. The processor 5 can include an image processor 6 and a central processing unit (CPU) 7. The image processor 6 performs image processing on frames of image data received from an infrared camera included within the heat detector 4. The image processor 6 can include a "Nuvision" image processing work station which is a "Nubus" card compatible with a MacIntosh 2X computer.

The processed frames of image data can be provided from the image processor 6 to a memory 8 under control of the CPU 7. In addition to storing the processed frames of image data, the memory 8 can be used to store the heat signal in the form of frames of image data before processing by the image processor 6. The processed frames of image data can be compiled into "tiles" and the tiles stored in the memory 8. An input device 9 allows an operator to specify certain parameters for image processing, to initiate an analysis of the material 3 using the thermographic unit 1, and/or to manipulate the display of tiles on a display unit 10, for example. The CPU 7, the memory 8, the input device 9 and the display unit 10 can be realized, for example, using a MacIntosh 2X computer.

In operation, to initiate an analysis of the material 3 using the thermographic unit 1, the input device 9 which can be a keyboard, for example, is operable by an operator to cause the CPU 7 to activate the heat source 2. Specifically, the CPU 7 can be interfaced with the heat source 2 using a MacAdios Nubus card which functions to output a signal to a gate terminal of a field effect transistor (FET) having channel terminals coupled to respective terminals of a photographic flash lamp included within the heat source 2. By activating the FET with the signal, the photographic flash lamp is activated and the resulting flash heats the material 3.

The heat detector 4 generates a heat signal over time in response to

heat emanated from the material 3 as the material 3 cools. In the case in which the heat detector 4 is implemented as an infrared camera, the heat signal is composed of sequential frames of image data which are periodically obtained by the infrared camera. These frames of image data can be provided to the memory 8 or processed directly in real time by the image processor 6. In either case, because thermal flow in a material is a relatively slow phenomenon, it is desirable to improve the quality of images derived from the frames of image data by averaging several frames of image data to obtain a tile. This processing of the frames of image data performed by the image processor 6 is described below with reference to Figure 4.

In Figure 4, image processing by the image processor 6 begins at step S1. In step S2, various parameters are set to initial values. Specifically, i is set equal to the number of frames to be averaged per tile, k is set equal to the total number of frames of image data to be processed, the dummy variable m is set equal to zero and n is set equal to k divided by i. Accordingly, n is the total number of tiles to be obtained for a given analysis of the material 3.

In step S3, i successive frames of image data are averaged to obtain a tile m. In other words, the corresponding pixel values (of, e.g., 8-bits) for i frames are added together, and the resulting pixel values are divided by i. The tile m, like each frame of image data, is thus a two-dimensional array of data corresponding to an image at a particular average depth within the material 3. This tile m is stored in step S4, and a decision is made in step S5 to determine whether m is equal to the total of tiles n, a condition which indicates the end of the operation for compiling tiles indicated in Figure 4. If m does not equal n, m is incremented by one in step S6 and steps S3-S5 are repeated. On the other hand, if m is equal to n in step S5, processing can either be terminated at step S7 of Figure 5, or further processing can be initiated, as indicated in the flow chart of Figure 6.

The processing of Figure 6 serves to eliminate a background image which is not useful in diagnosing a feature of interest in the material 3.

Therefore, in Figure 6, the processing for subtracting the last (i.e., coolest) tile n from all other tiles and itself begins by setting the dummy variable m to zero in step S8. In step S9, the value of each pixel in the array of tile n is subtracted from a corresponding pixel in tile m. The tile m resulting from step S9 is stored in step S10. In step S11, a decision is made to determine whether m is equal to n, which indicates the completion of the operation to eliminate the background image from all of the tiles. If m is not equal to n, processing proceeds to step S12 in which m is incremented by one, and steps S9-S11 are repeated. On the other hand, if m is equal to n in step S11, image processing terminates at step S12 in Figure 7, or alternatively, further processing can be performed at step S14 of Figure 8.

In Figure 8, the dummy variable m is set equal to zero in step S14. Also, in step S14, j is set equal to the number of a particular tile to be used for normalization. Usually, j is set equal to one of the earliest tiles corresponding to relatively higher temperatures. By trial and error, j can be set equal to the number of a tile which yields a display which is optimum or at least adequate for analyzing the material 3.

In step S15, the pixels of the array included within tile m are divided by corresponding elements of the array of tile j to normalize tile m. In step S16, the normalized tile m is stored in the memory 8 under the control of the CPU 7, and a decision is made to determine whether m is equal to n in step S17. If m is not equal to n, in step S18, m is incremented by one and steps S15-S17 are repeated. On the other hand, in step S17, if m is equal to n, the last tile has been normalized and stored in the memory 8, and processing terminates at step S19.

While specific types of processing of the heat signal executed by the processor 5 have been described above with respect to Figures 4-8, a part of the processing employed in Figures 4-8, or other processing, conventional or otherwise, can be used to condition the heat signal received from the heat detector 4.

With the image processing employed in Figures 4-8, a series of tiles is obtained. Each tile is a thermographic image at a depth within the material 3 corresponding to the number of the tile. Therefore, the tiles 0-n are thermographic images at 0-n increments of depth within the material 3. Using the thermographic unit 1 of Figure 3, tiles can be selected using the input device 9 to generate a display on the display unit 10. Thus, an operator can scan and evaluate a feature at a selected depth within the material 3, depending upon the tile selected to generate the display on the display unit 10.

To determine the depth increment corresponding to each tile, the following equation can be used:

(1) $l = \sqrt{t \times \alpha}$,

where l is the distance travelled by heat in the material 3, t is the time elapsed from rapid heating of the material 3 to detection of heat which is back-scattered in the material 3 so that such heat travels a total distance l, and α is the diffusivity of the material 3. Assuming that the heat detector 4 generates a heat signal of 30 frames of image data per second, and assuming that the total distance traveled by heat in the material 3 is equal to twice the depth of interest, l_D, because the heat travels into the material 3 to the depth l_D and is back-scattered to travel back toward the surface of the material 3, t is equal to i/30 and l is equal to $2l_D$. Substituting these values into equation (1) yields:

(2) $$l_d = \frac{\sqrt{\alpha \times i}}{10.95} .$$

Therefore, the depth corresponding to each tile is $(m \times l_D)/2$ where m is the tile number.

There are many techniques which can be used to determine the diffusivity α of a material. One such technique uses an oscillating thermal source to heat a sample of the material 3 having a known thickness q. A

phase difference ϕ is measured between the heat present at one side and the heat present at an opposite side of the sample. The phase difference ϕ is defined by the following equation:

$$(3) \qquad \phi = \frac{\pi}{4} + \frac{\sqrt{2}}{2} pq - \tan\left[\frac{e^{-\sqrt{2}qp}\sin\sqrt{2}qp}{e^{-\sqrt{2}qp}\cos\sqrt{2}qp}\right].$$

The parameter p is defined as:

$$(4) \quad p = \sqrt{\frac{w}{\alpha}}.$$

Because the phase difference ϕ of heat present at either side of the material, the thickness q of the material and the frequency ω of the oscillating thermal source are known quantities, a guess can be made as to the value of the diffusivity α to derive a value for the parameter p in equation (4). The resulting value of the parameter p from equation (4) can be substituted into equation (3) together with the value for the thickness q to obtain a guessed value of the phase difference ϕ. By comparing the guessed value of the phase difference ϕ and the measured value of the phase difference ϕ, another estimate for the value α can be determined, if necessary. Accordingly, by trial and error, the diffusivity α can be determined to a desired degree of precision within the limits of the equipment used to determine the diffusivity α. It should be noted, however, that the technique for determining the diffusivity α described above is but one example, and that other techniques can be used to determine the diffusivity α.

Figure 9 is a diagram of an ultrasonic unit 11 used for specifically locating a feature in the material 3 for quantification and/or evaluation of the feature. The ultrasonic unit 11 can be used to provide a more detailed analysis of a feature detected or generally located by the thermographic unit 1. Therefore, using the thermographic unit 1 and the ultrasonic unit 11 in tandem, rapid detection and effective quantification and/or evaluation of a feature such

as, for example, damage or a defect, can be performed.

The ultrasonic unit 11 includes an ultrasonic transmitter 12 arranged in proximity to the material 3, which generates an ultrasonic signal to the material 3. Scattering of the ultrasonic signal occurs at a continuum of depths within the material 3, and the resulting echo is received by an ultrasonic receiver 13. The ultrasonic receiver 13 generates a received signal based on the echo, and provides the received signal to a processor 14. The ultrasonic receiver 13 can be incorporated together with the ultrasonic transmitter 12 as a conformable array of transducers spaced at equal x-y positional increments in a mat of a flexible material, and sequentially monitored by the processor 14. Accordingly, the conformable array can be used on surfaces of the material 3 which are curved or irregular. Alternatively, the ultrasonic receiver 13 can include a raster scan transducer which is deflected to x-y positions sequentially and monitored under control of the processor 14.

The processor 14 functions to generate a display based on the received signal, or to generate data which can be quantified and/or evaluated by an external device suited for such purpose. The processor 14 can include a sampler/digitizer 15 which samples and/or digitizes the received signal, and a central processing unit (CPU) 16 which generates the display based on the sampled and/or digitized received signal from the sampler/digitizer 15. Preferably, the sampler/digitizer 15 generates successive frames of image data periodically so that each frame of image data is a two-dimensional array of pixels corresponding to an ultrasonic image of the material 3 at a certain depth which depends upon the time elapsed from generation of the ultrasonic signal to reception of the echo back-scattered from the certain depth within the material 3. Accordingly, the successive frames of image data are ultrasonic images at increments of depth in the material 3. The successive frames of image data define a three-dimensional array corresponding to x-y positions and depth, which can be stored in a memory 17 under control of the CPU 16. An input device 18 such as , for example, a keyboard, can be manipulated by an

operator to cause the CPU 16 to generate a display based on the image data stored in the memory 17. In other words, by manipulating the input device 18, the operator can select a frame of image data to generate the display on the display unit 19. Accordingly, the operator can specifically locate a feature such as, for example, damage or a flaw, to effectively quantify and/or evaluate the feature based on the frames of image data.

The CPU 16, the memory 17, the input device 18 and the display unit 19 can be implemented as elements of a MacIntosh 2X computer, for example. It should also be noted that the processor 14 of the ultrasonic unit 11 of Figure 9 can be implemented to include the processor 5 of the thermographic unit 1 of Figure 3 to reduce the amount of equipment needed to realize the combination of the thermographic unit 1 and the ultrasonic unit 11.

The operation of the thermographic 11 of Figure 9 is now explained with reference to Figure 10. In Figure 10, operation of the ultrasonic unit 11 begins in step S51. In step S52, the dummy variable m is set to zero, a dummy variable s is set equal to zero, v is set equal to the last depth for each x-y position to be analyzed relative to the surface of the material 3 and w is set equal to the number corresponding to the last x-y position to be analyzed relative to the surface of the material 3. Therefore, v can correspond to the last transducer in the conformable array of transducers from which data is to be taken, or v can correspond to the last x-y position of a raster scan transducer included within the ultrasonic receiver 13.

Under control of the CPU 16, the ultrasonic transmitter 12 transmits an ultrasonic pulse $\delta(t)$ to the material 3 in step S53. The ultrasonic pulse $\delta(t)$ is back-scattered over a continuum of depths of the material 3 and, based on the resulting echo, the ultrasonic receiver 13 generates a received signal which is provided to the processor 14. In the processor 14, the sampler/digitizer 15 samples the received signal in step S54 to obtain a measured response sequence f(m), where m is an integer representing a period of time. Because the rate of propagation of the ultrasonic pulse in the material 3 is relatively

constant, the period of time m is directly proportional to the depth at which back-scatter is observed in the material 3.

An input sequence g(m) can be determined, for example, by transmitting the ultrasonic pulse $\delta(t)$ to a solid metal plate and sampling the echo. Therefore, because f(m) and g(m) are known, the material transfer function h(m) can be determined by deconvolution. Accordingly, in step S55, the measured response f(m) is deconvolved to obtain the material transfer sequence h(m) using the CPU 16. Because the material transfer sequence h(m) represents only the real part of the analytic material transfer sequence $h_A(m)$, the CPU 16 performs a Hilbert transform on the material transfer sequence h(m) in step S56, to obtain the Hilbert transform of the material transfer sequence, Hi{h(m)}. By taking the magnitude of the analytic material transfer sequence $h_A(m)$, the CPU 16 determines the magnitude of the analytic material transfer sequence $|h_A(m)|$ in step S57 according to the equation:

$$(5) \quad |h_A(m)| = [h(m)^2 + (Hi[h(m)])^2]^{1/2}$$

In step S58, a decision is made to determine whether m is equal to the time corresponding to the last depth for which image data is to be obtained at an x-y position s in the material 3. If m is not equal to v, m is incremented by one in step S59 and steps S53-S58 are repeated. On the other hand, if m is equal to the n, a decision is made in step S60 to determine whether s is equal to w, the last x-y position to be analyzed relative to the surface of the material 3. If s is not equal to w, in step S61, s is incremented by one and, in step S62, the CPU 16 prepares analyze the next x-y position by switching to the next transducer of the conformable array, or by deflecting a raster scan transducer to the next x-y position, for example. On the other hand, in step S59, if s is equal to the number of the last x-y position w, the CPU 16 terminates processing in step S63. The result of the processing of Figure 10 is a series of image data including pixel values for x-y positions 0-w at successive depths

0-n in the material 3.

Figure 11 is a graph of the magnitude of the analytic transfer sequence $h_A(m)$ versus m. In other words, Figure 11 represents the response of the material 3 from various depths A-H within the material 3 at a particular x-y position relative to the surface of the material 3. The largest peaks correspond to the front and back surface of the material 3.

In Figure 12, a series of image data for the depths A-H of Figure 11, exhibit typical dumbbell shapes of delaminations within the material 3, which in this case is the flat panel of Figure 1. By manipulating the input device 18 of Figure 9, an operator generate a display of the image data stored in the memory 17 on the display unit 19 of Figure 9. Accordingly, the operator can specifically locate a feature such as, for example, damage or a defect in the material 3 by viewing the display of image data on the display unit 19.

In Figure 13, thermographic and ultrasonic displays generated with the image data indicate damage caused by various impact energies (i.e., 14, 27 and 41 Joules) of an aluminum ball on the flat panel of Figure 1. As shown in Figure 13, the thermographic unit 1 is effective for detecting and/or generally locating the damage in the flat panel. However, the thermographic displays are not particularly effective for quantifying or specifically locating the damage in the flat panel of Figure 1. Accordingly, using the ultrasonic unit 11, the damage to the flat panel can be more readily quantified and/or evaluated using the ultrasonic displays.

Figure 14 is a diagram of a conceivable realization of the thermographic unit 1 of Figure 3. The heat source 2 is implemented as two separate photographic flash lamps which are disposed at roughly the same angle relative to the surface (i.e., the material 3) of the helicopter 20 to uniformly heat a material surface of the helicopter 20. The heat detector 4 is implemented as an infrared camera which provides the heat signal to portable unit 21 which contains the processor 5, the memory 8, the input device 9 and the display unit 10 of Figure 3. Therefore, by moving the heat source 2 and infrared camera

4 relative to the helicopter 20, a feature such as, for example, damage in the material 3 composing the helicopter 20 can be detected and/or generally located. Any damaged areas can be marked by an operator for ultrasonic analysis.

In Figure 15, a feature detected and/or generally located by the thermographic unit 1 can be analyzed using an ultrasonic transmitter 12/ultrasonic receiver 13. In Figure 15, the ultrasonic receiver 12/ultrasonic receiver 13 are implemented as a conformable array of transducers which are used to specifically locate a feature such as damage on material surfaces of the helicopter 20. The ultrasonic transmitter 12/ultrasonic receiver 13 are coupled to the portable unit 21 which includes the processor 14, the memory 17, the input device 18 and the display unit 19 of Figure 9.

In Figures 14 and 15, the thermographic unit 1 and the ultrasonic unit 11 require elements on only one side of the helicopter 20. In other words, equipment is not needed inside or on the opposite side of the helicopter 20, and therefore, the thermographic unit 1 and the ultrasonic unit 11 provide relatively simplified scanning of a feature in the material composing the helicopter 20. Also, the thermographic unit 1 and the ultrasonic unit 11 are relatively portable, and less expensive relative to conventional NDE devices and techniques.

Numerous modifications and adaptions of the present invention will be apparent to those skilled in the art and thus, it is intended by the appended claims to cover all modifications and adaptions which follow in the true spirit and scope of the invention and equivalents thereof.

What is claimed is:

RAPID DETECTION AND QUANTIFICATION OF FEATURES SUCH AS DAMAGE OR FLAWS IN COMPOSITE AND METALLIC STRUCTURES

Abstract of the Disclosure

An apparatus, system and method for non-destructive evaluation (NDE) of a material use thermography to rapidly detect and/or generally locate a feature such as, for example, damage or a defect in the material. The apparatus, system and method also use ultrasound to specifically locate the feature in the material for quantification and/or evaluation either by an operator or by an external device suited for such purpose. Accordingly, the apparatus, system and method are particularly useful for NDE in applications such as the analysis of the structure of an aircraft, for example, in which the scale of the material to be analyzed is large, thus requiring the rapid NDE afforded by thermography, and in which quantification and/or evaluation of a feature must be performed with precision, thus requiring the relatively high-resolution NDE afforded by ultrasound.

FIG. 1

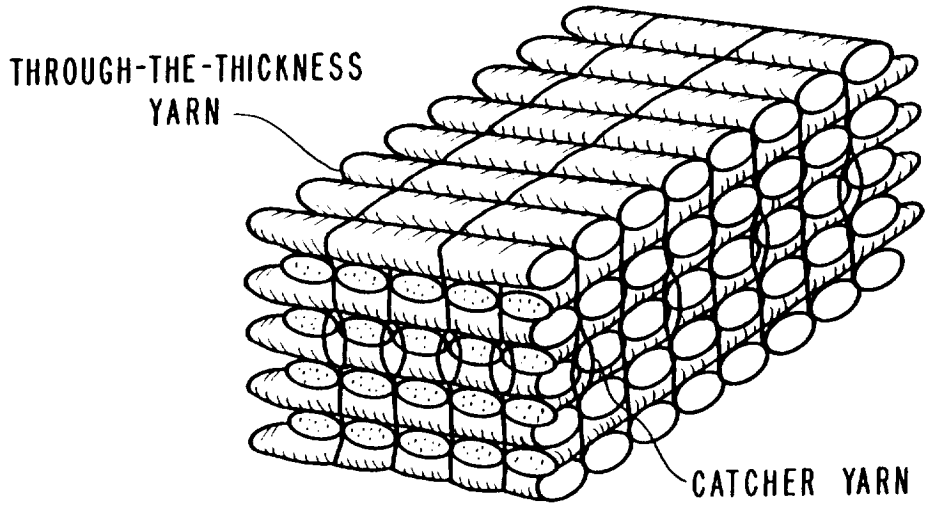
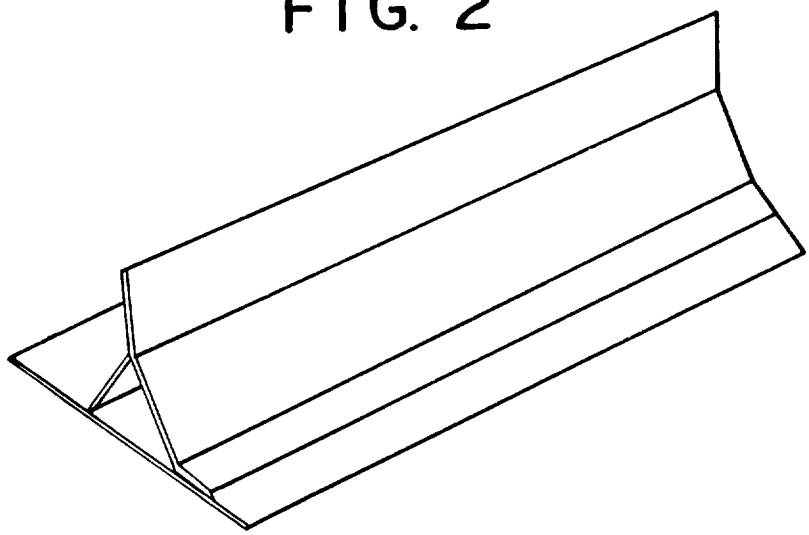


FIG. 2



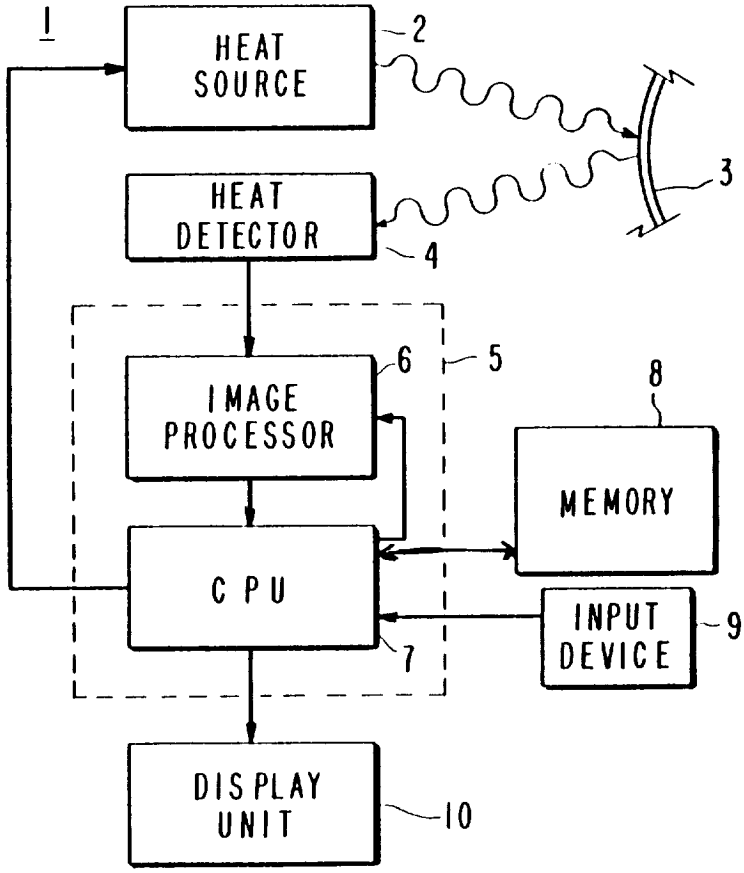

1
HEAT SOURCE
2
3
HEAT DETECTOR
4
5
6
IMAGE PROCESSOR
8
MEMORY
C P U
7
INPUT DEVICE
9
DISPLAY UNIT
10

FIG. 3

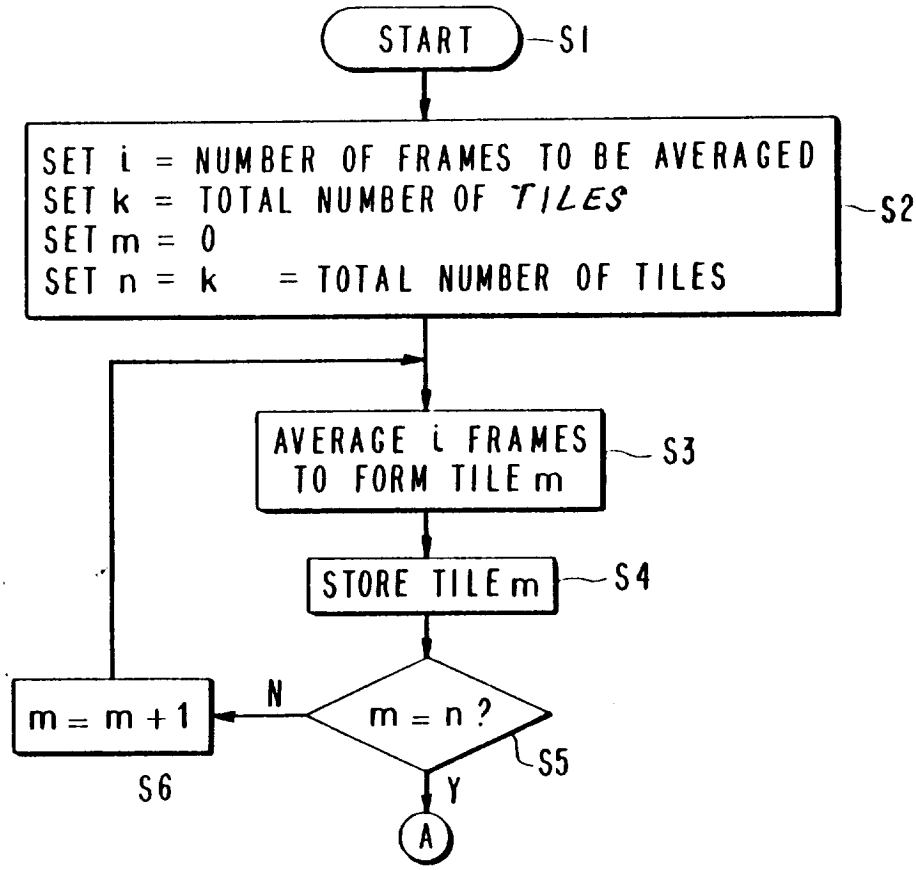

START
S1
SET i = NUMBER OF FRAMES TO BE AVERAGED
SET k = TOTAL NUMBER OF TILES
SET m = 0
SET n = k = TOTAL NUMBER OF TILES
S2
AVERAGE i FRAMES TO FORM TILE m
S3
STORE TILE m
S4
m = n ?
S5
N
m = m + 1
S6
Y
A

FIG. 4

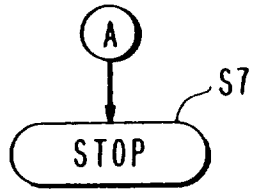


FIG. 5

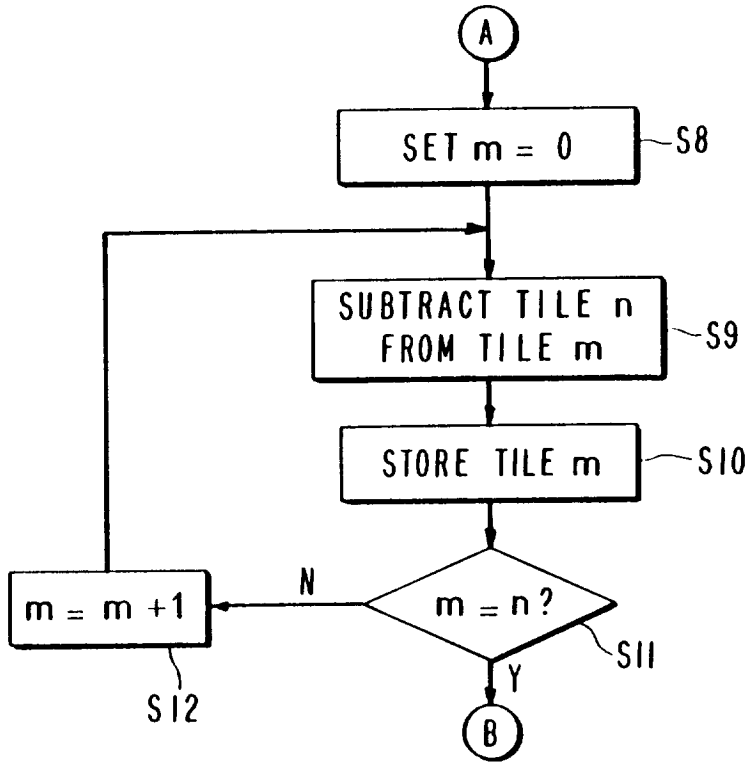


FIG. 6

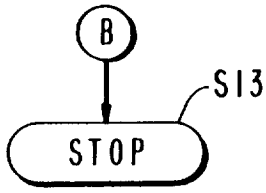


FIG. 7

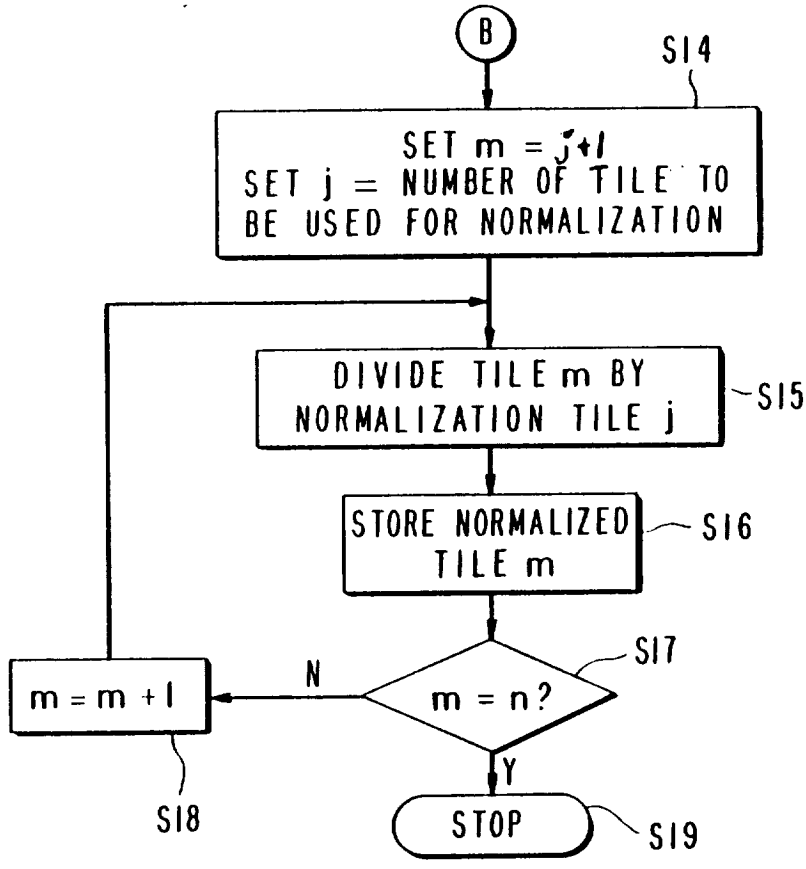


FIG. 8

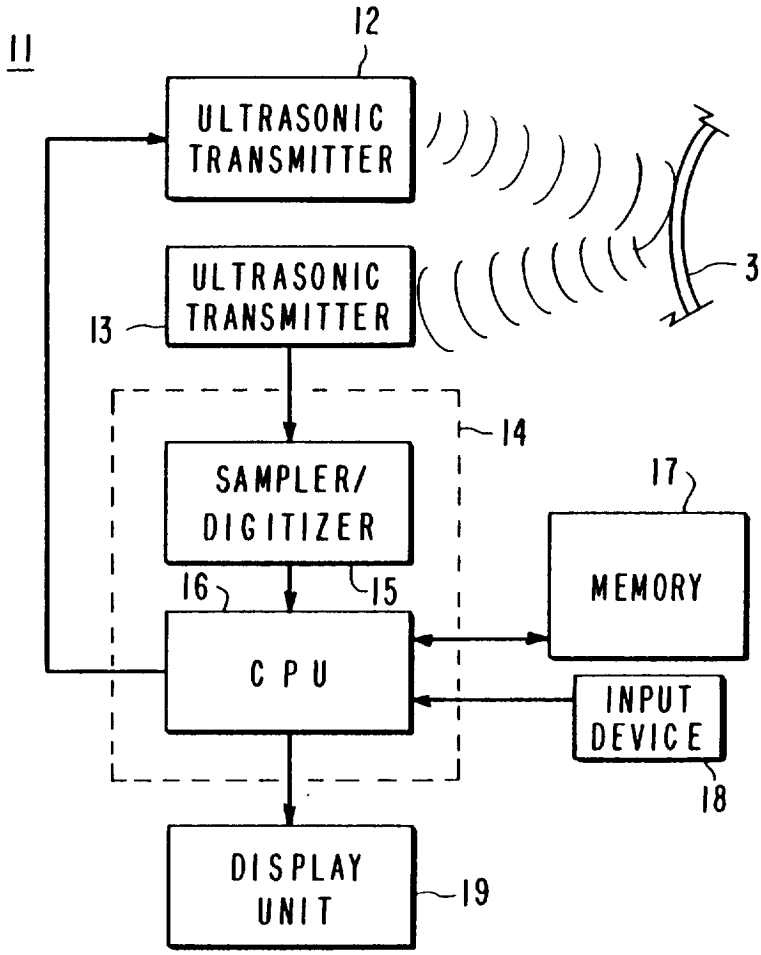
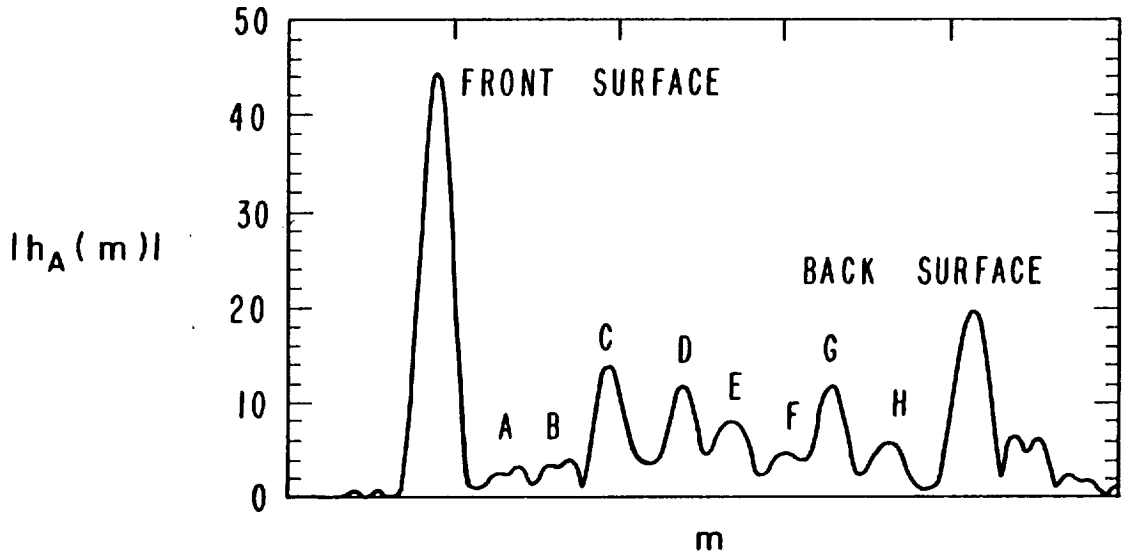


FIG. 9



$|h_A(m)|$

FIG. 11

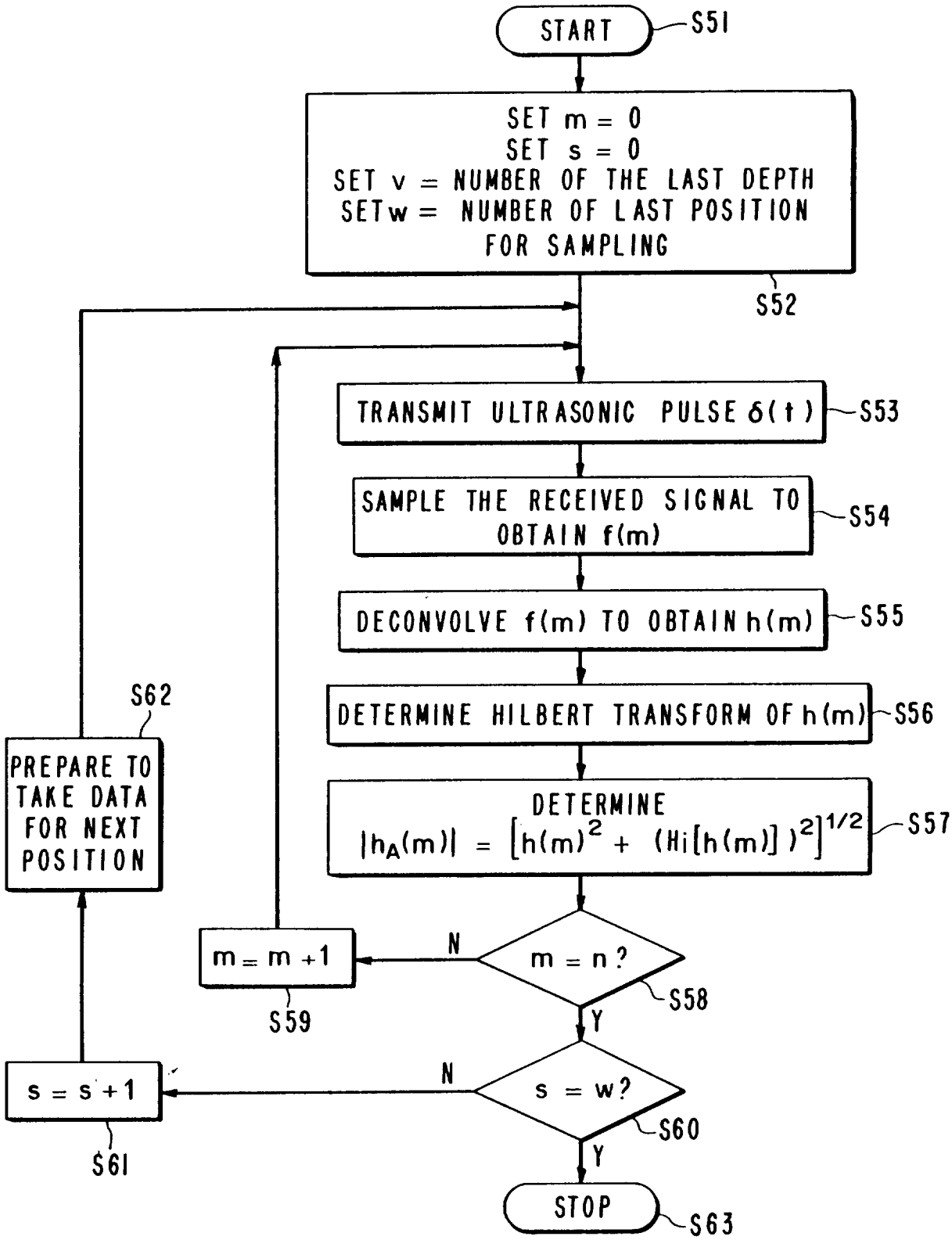

START
S51
SET m = 0
SET s = 0
SET v = NUMBER OF THE LAST DEPTH
SETw = NUMBER OF LAST POSITION FOR SAMPLING
S52
TRANSMIT ULTRASONIC PULSE δ(t)
S53
SAMPLE THE RECEIVED SIGNAL TO OBTAIN f(m)
S54
DECONVOLVE f(m) TO OBTAIN h(m)
S55
DETERMINE HILBERT TRANSFORM OF h(m)
S56
DETERMINE
$|h_A(m)| = [h(m)^2 + (Hi[h(m)])^2]^{1/2}$
S57
m = n ?
S58
N
m = m +1
S59
Y
s = w?
S60
N
s = s +1
S61
Y
STOP
S63
S62
PREPARE TO TAKE DATA FOR NEXT POSITION

FIG. 10

FIG. 12

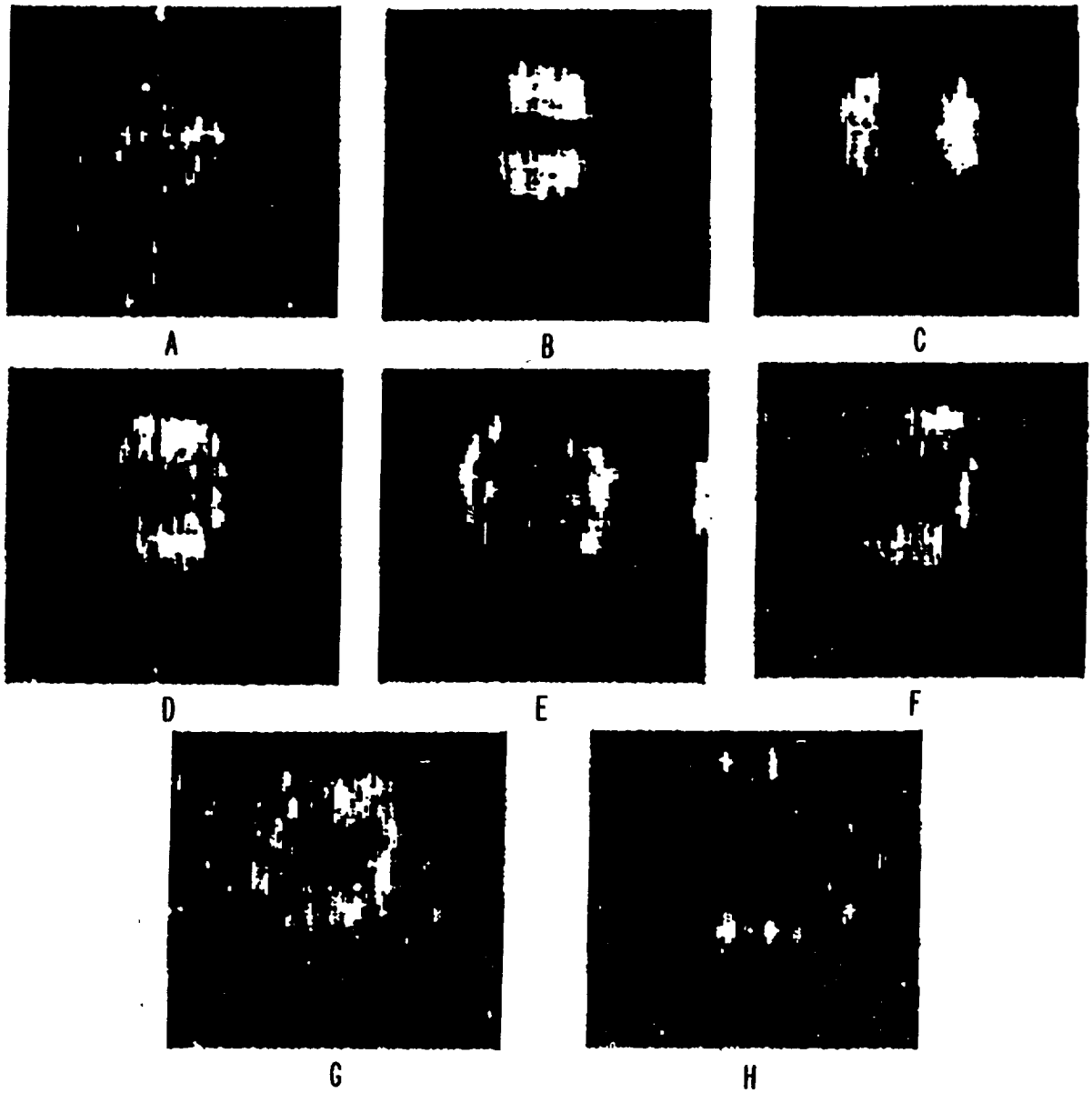


FIG. 13

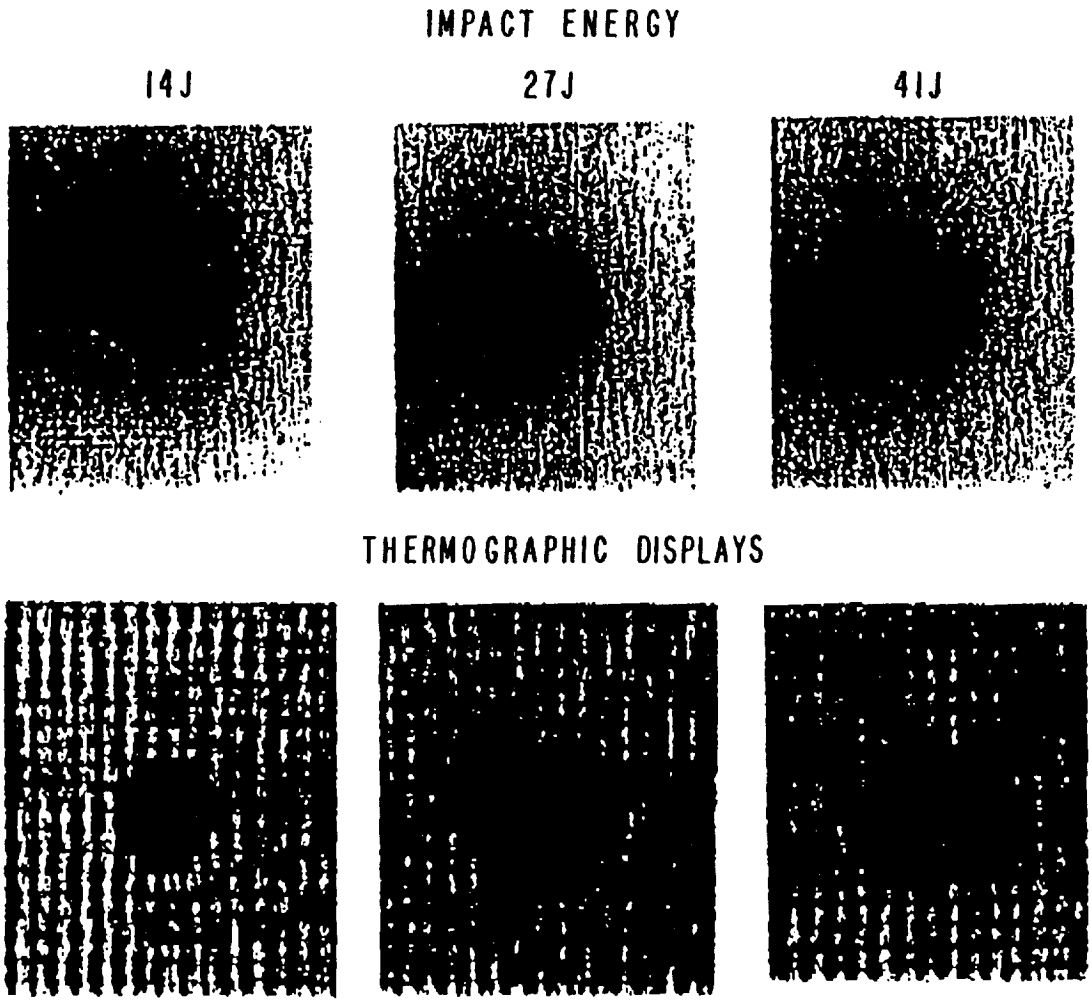

IMPACT ENERGY
14J
27J
41J
THERMOGRAPHIC DISPLAYS
ULTRASONIC DISPLAYS

FIG. 14

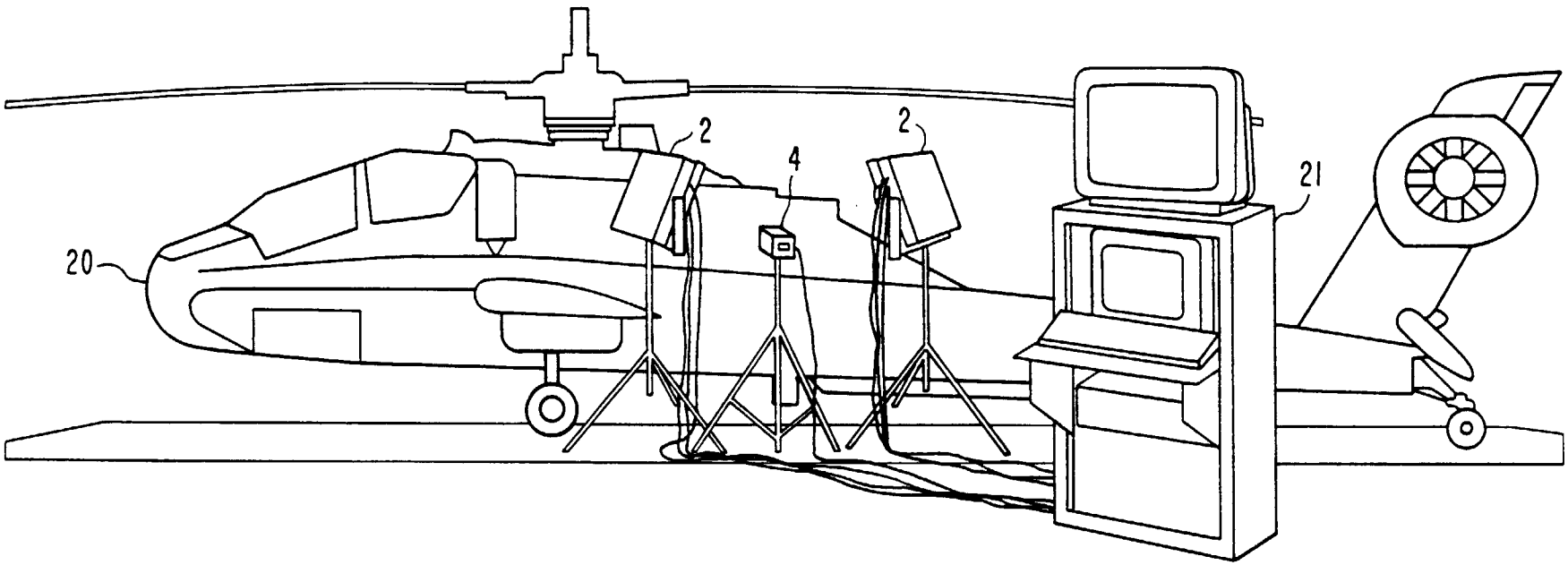


FIG. 15